ICBEST 2014
Building for a Changing World

Variable density concrete walls engineered for energy performance

Larry A. Bellamy[1]

[1]RMIT University, Melbourne, Australia
Corresponding author: Larry A. Bellamy, larry.bellamy@rmit.edu.au

Abstract

This paper investigates the energy performance of variable density concrete wall panels that combine the thermal insulation of a layer of lightweight concrete with the thermal mass of a layer of structural concrete. The effect of layer thickness and thermal conductivity on wall energy performance is assessed by determining the equivalent U-factors of different wall panel designs at eight temperate locations. The analysis indicates that variable density concrete panels can be engineered to achieve net-zero wall energy performance, although heat may have to be actively added to a panel in order to achieve this level of performance at cool locations. A simulation analysis of the energy performance of a house constructed with variable density wall panels is conducted using the ESP-r simulation program. This analysis indicates that variable density concrete wall panels are suitable for use in net-zero energy houses, especially in warm temperate locations.

1 Introduction

Stratified concrete is a new type of material being developed for the production of variable density concrete wall panels, that combine the thermal insulation provided by lightweight concrete with the thermal mass and strength provided by heavyweight concrete ([1], Mackechnie and Bellamy, 2013). Panels are cast from a single concrete mix comprising lightweight and heavyweight aggregates, which is vibrated to form lightweight and heavyweight layers, joined by a transition layer (Fig. 1). This technology was devised as a cost-effective way of producing energy efficient concrete cladding panels.

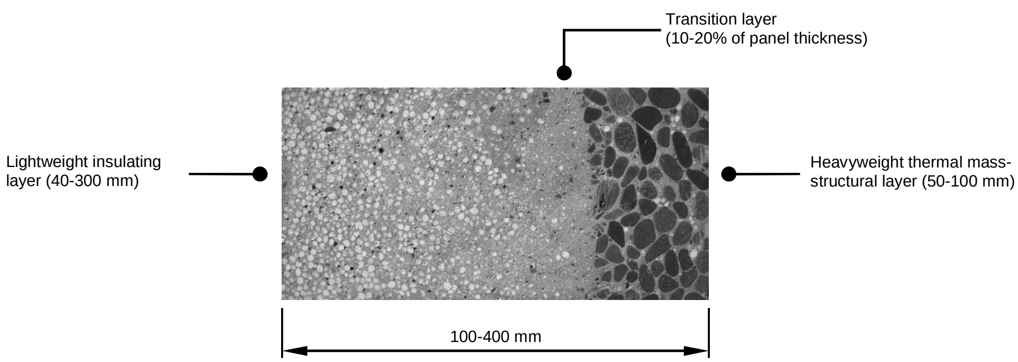

Figure 1. Cross-section of stratified concrete wall panel (rotated 90^{o} anticlockwise from casting position)

In-situ thermal tests undertaken by Mackechnie and Bellamy (2013) [1] provide experimental evidence of the energy performance of stratified concrete wall panels. Test results indicate the in-service energy performance of 250 mm thick stratified concrete panels (U-factor ~1.2 W/m^{2}K) and polystyrene panels (U-factor ~0.5 W/m^{2}K) are approximately equal, for north-facing walls at Christchurch (43.5 ^{o}S). The concrete panels' performance was enhanced by their thermal mass and closely matched that of lightweight walls with more than double the insulation of the concrete panels.

Limited information can be drawn from the Christchurch tests as only three wall designs were tested at the one location. The aim of this paper therefore, is to develop a better understanding of the energy performance of these walls by undertaking a simulation analysis to determine the relationship between wall design and performance, and how this varies with location. The analysis is limited to locations with temperate climates as stratified concrete walls are expected to be well-suited to these conditions.

2 Method

2.1 Equivalent U-factor

The ESP-r (v11.8) building simulation program was used to determine the relationship between selected wall design variables and the equivalent U-factor[1] of stratified concrete walls. The equivalent U-factor is a simple performance metric that accounts for the effects of thermal mass, solar heat gain and insulation on wall conduction and is a superior indicator of wall energy performance compared with the U-factor ([2], Bellamy, 2014).

Design variables included in the simulation analysis are: heavyweight layer thickness (50-100 mm); panel thickness (100-400 mm); heavyweight layer thermal conductivity (1.0-1.8 W/mK); and lightweight layer thermal conductivity (0.16-0.24 W/mK).

The values for thermal conductivity used in the analysis and the relationship between thermal conductivity and concrete density[2] are based on measurements from Mackechnie and Bellamy (2013) [1]. Thermal conductivity of the transition layer, specific heat capacity of concrete and solar absorptance are treated as constants equal to 0.3 W/mK, 900 J/(kg.^{o}C) and 0.6 respectively. The thickness of the transition layer is set equal to 15% of panel thickness.

Equivalent U-factors are determined for stratified concrete walls at the locations listed in Table 1. These locations represent a wide range of temperate climates, including maritime (Christchurch, Wellington, Melbourne, Auckland and Sydney), Mediterranean (Adelaide and Perth) and humid subtropical (Brisbane). East-, west-, north- and south-facing walls are included in the analysis in order to assess the effect of wall orientation on equivalent U-factors.

Table 1. Typical year climate statistics[3] of selected temperate locations.

Location	Latitude (^{o}S)	Annual mean air temp (^{o}C)	Annual mean global solar radiation (MJ/(m^2.day))	Annual 18 ^{o}C heating degree days (degree-day)	Annual 22 ^{o}C cooling degree days (degree-day)
Christchurch	43.5	11.3	13.1	2583	42
Wellington	41.4	12.8	13.9	1966	2
Melbourne	37.8	15.0	14.4	1506	175
Auckland	37.0	15.3	14.7	1222	26
Adelaide	34.9	17.0	17.6	1181	419
Sydney	33.8	18.4	17.4	632	229
Perth	32.0	18.0	18.7	911	429
Brisbane	27.4	19.9	17.9	482	396

[1] Defined as the apparent U-factor when the adjacent building space requires auxiliary heating or mechanical cooling. The $U_{eqV18\text{-}10}$ variant of the equivalent U-factor ([2], Bellamy, 2014) is used in this paper. It is determined by simulating wall conduction over a typical meteorological year with prescribed indoor air temperatures (18-22 ^{o}C varying diurnally) and heating and cooling periods.

[2] The thermal conductivity k (W/mK) and density ρ (kg/m^3) of concrete are related by:

$k = 0.00064\rho - 0.31$ if $\rho \leq 1800$ kg/m^3; or

$k = 0.00114\rho - 1.21$ if $\rho > 1800$ kg/m^3.

[3] From NIWA and RMY climate data files available at: http://apps1.eere.energy.gov/buildings/energyplus.

2.2 Wall energy performance

Wall energy performance is defined here as the thermal load imposed on heating and mechanical cooling equipment due to conduction within an opaque wall(s). The ESP-r (v11.8) program was used to determine the mean energy performance of the external walls in a 165 m^2 model house (Fig. 2) over a typical meteorological year. The model house was simulated firstly with stratified concrete external walls and then with fictitious non-conducting walls, enabling the mean energy performance EP (J/m^2) of stratified concrete walls to be found from:

$$\mathrm{EP} = \frac{Q_{aux}\text{-}Q_{aux,0}}{A_w} \tag{1}$$

where Q_{aux} (J) is the heating and cooling load of the house with 'real' walls, $Q_{aux,0}$ (J) is the heating and cooling load with adiabatic and non-absorbing (i.e. zero solar heat gain) walls and A_w (m^2) is wall area. Similar approaches to the above have been used to define the energy performance of windows ([3], Grynning et al., 2013).

Key simulation parameters of the model house are given in Table 2.

Table 2. Model house simulation parameters.

Parameter	Value/description
Floor design	100 mm insulated concrete slab-on-ground (U-factor ~0.3 W/m^2 K)
Roof design	Timber frame with horizontal plasterboard lining (U-factor ~0.3 W/m^2 K)
External wall design	Stratified concrete panels (see Sec. 2.1)
Internal wall design	90 mm timber frame lined with 10 mm plasterboard Note: internal garage walls are stratified concrete panels
Window design	Double-glazed (U-factor ~3.8 W/m^2 K)
Window area	25% of total wall area (uniformly distributed around house)
Solar shading	600 mm wide eaves (wider over entrance)
Floor coverings	Ceramic tiles in living, dining and kitchen and carpets in rest of house
Solar absorptance	0.8 for roof; 0.6 for walls
Infiltration rate	0.5 ach
Cooling ventilation rate	6 ach maximum
Internal heat gain	4 W/m^2 from 10 pm to 8 am; 8 W/m^2 from 8 am to 10 pm
Heater capacity	Infinite
Mechanical cooler capacity	Infinite
Heating temperatures	16 ^{o}C/19 ^{o}C from 11 pm to 7 am/ 7 am to 11 pm
Cooling temperatures	24.5 ^{o}C ventilation cooling; 25 ^{o}C mechanical cooling

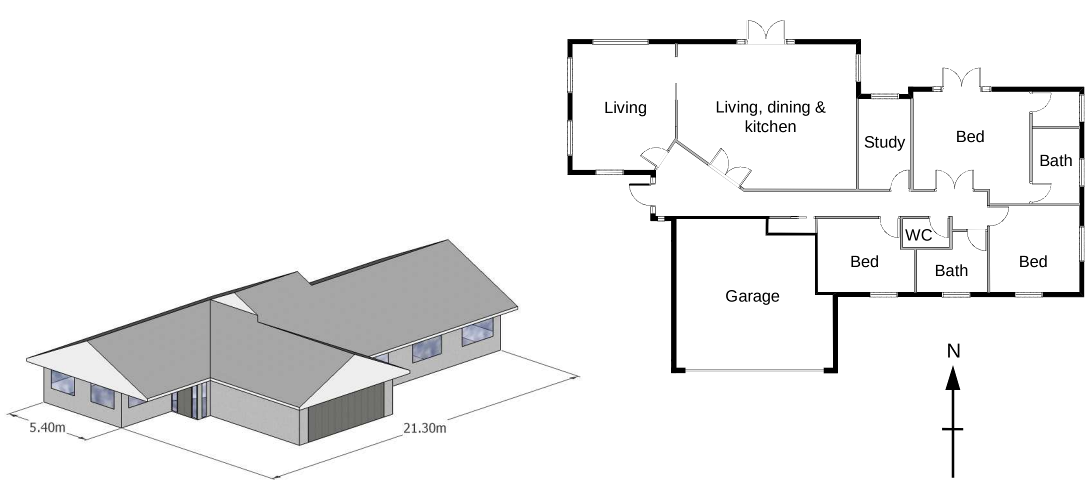

Figure 2. Model house floor plan

3 Results

3.1 Equivalent U-factor

Panel thickness and the thickness of the heavyweight layer are key variables in the structural and energy design of stratified concrete walls. Figure 3 shows equivalent U-factors (U_{eq}) and U-factors (U) of 100-400 mm thick north-facing panels at the locations listed in Table 1. Both U_{eq} and U reduce with increasing wall thickness but reductions in U_{eq} are much greater as this metric accounts for wall thermal mass. U_{eq} values less than zero can be observed at all locations in Figure 3, indicating 'plain' stratified concrete walls can be designed to be net-zero energy, i.e. conduction in these walls actually reduces annual energy demand of a building. Panel thickness required to achieve $U_{eq} \leq 0$ depends on location and thermal conductivity of the lightweight layer. At Christchurch it appears 250-350 mm panels are required while 175-225 mm panels are required at warmer locations.

The relationship between heavyweight layer thickness and U_{eq} depends on location and panel thickness. Figure 3 shows that for panels thinner than 250-300 mm, a 50 mm thick heavyweight layer produces lower values of U_{eq} than a 100 mm layer. For panels thicker than 250-300 mm, a 100 mm heavyweight layer produces lower values of U_{eq}, except at Christchurch and Wellington. The optimal heavyweight layer thickness in terms of minimising U_{eq} depends on location, panel thickness and thermal conductivity of the lightweight layer.

Figure 3 shows that U_{eq} is reduced by reducing the thermal conductivity of the lightweight layer. In contrast Figure 4 shows that U_{eq} is reduced by increasing the thermal conductivity of the heavyweight layer. It can be seen from this figure that thermal conductivity of the heavyweight layer has little effect on U_{eq} at Christchurch but has a significant effect at Brisbane, where cooling is the dominate load.

Figure 4 also shows the relationship between U_{eq} and wall orientation for 200-400 mm thick panels at Christchurch and Brisbane. Variations with orientation are small for 400 mm panels but are greater for thinner panels, especially at Brisbane.

3.2 Wall energy performance

Net-zero energy walls (i.e. EP≤0) seems an appropriate minimum performance target for future buildings. It appears from Figure 3 that 250 mm thick stratified concrete walls can achieve this level of performance at most locations. Mean energy performances of 250 mm thick stratified concrete walls in the model house over a typical year are shown in Table 3. Performances are shown for 'low' specification stratified concrete, with thermal conductivities equal to 0.24 W/mK and 1.0 W/mK for the lightweight and heavyweight layers respectively, and 'high' specification stratified concrete with thermal conductivities equal to 0.16 W/mK and 1.8 W/mK for the two layers.

Table 3. Mean energy performance of 250 mm thick stratified concrete walls in the model house over a typical year (heavyweight layer thickness equals 75 mm).

	Wall energy performance ($MJ/(m^2.annum)$)	
Location	Low specification material[4]	High specification material[5]
Christchurch	44.3	24.7
Wellington	17.4	4.6
Melbourne	-14.9	-21.3
Auckland	-29.7	-31.8
Adelaide	-27.6	-31.5
Sydney	-52.4	-50.5
Perth	-44.7	-44.7
Brisbane	-43.9	-42.2

[4] k=0.24/1.0 W/mK and ρ=859/1938 kg/m^3 for the lightweight/heavyweight layer.
[5] k=0.16/1.8 W/mK and ρ=734/2640 kg/m^3 for the lightweight/heavyweight layer.

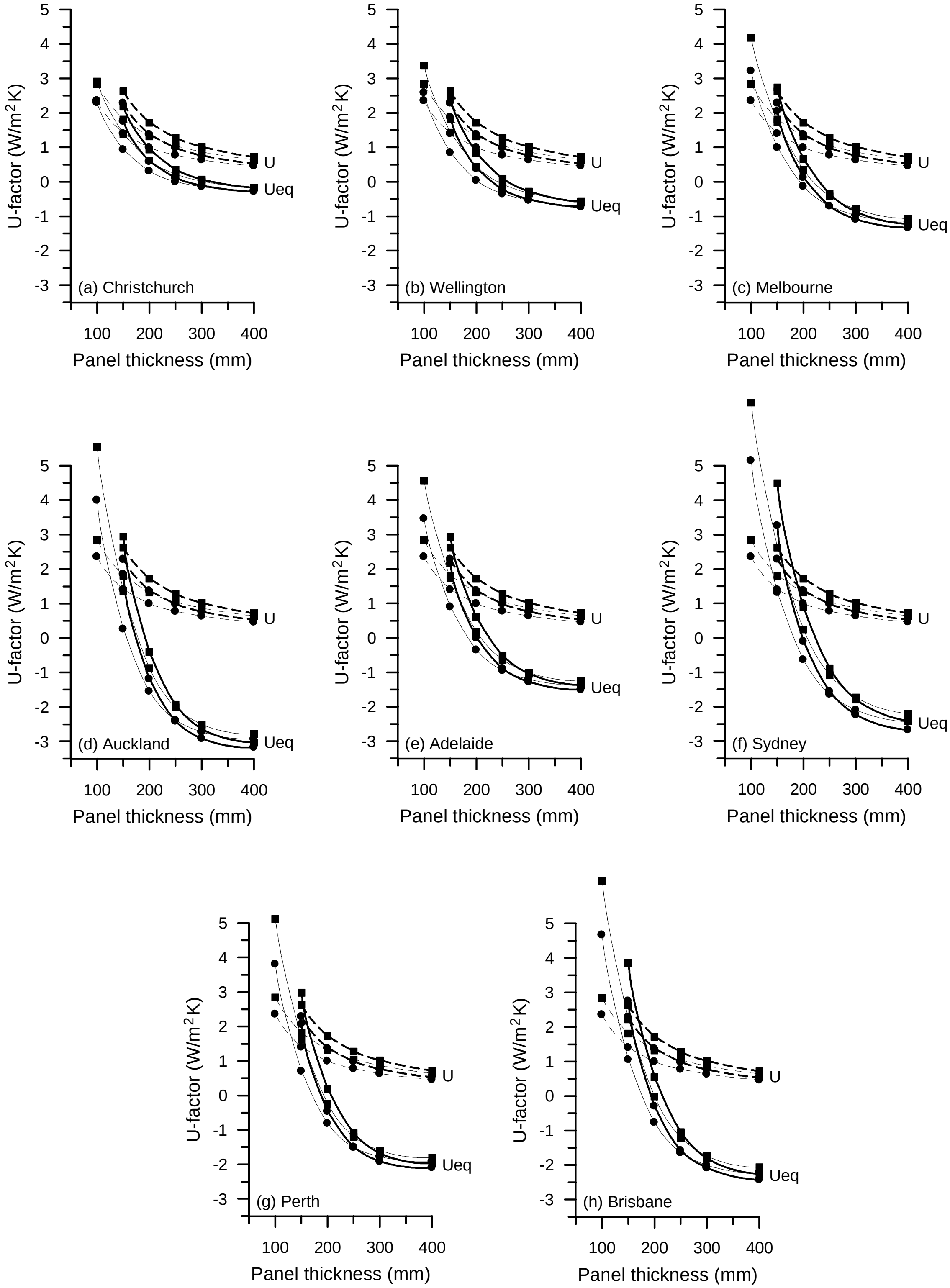

Figure 3. Equivalent U-factor (U_{eq}) and U-factor (U) of north-facing stratified concrete walls versus panel thickness (heavyweight layer thermal conductivity equals 1.4 W/mK; lightweight layer thermal conductivity equals 0.16 W/mK (●) or 0.24 W/mK (■); and heavyweight layer thickness equals 50 mm (─) or 100 mm (━))

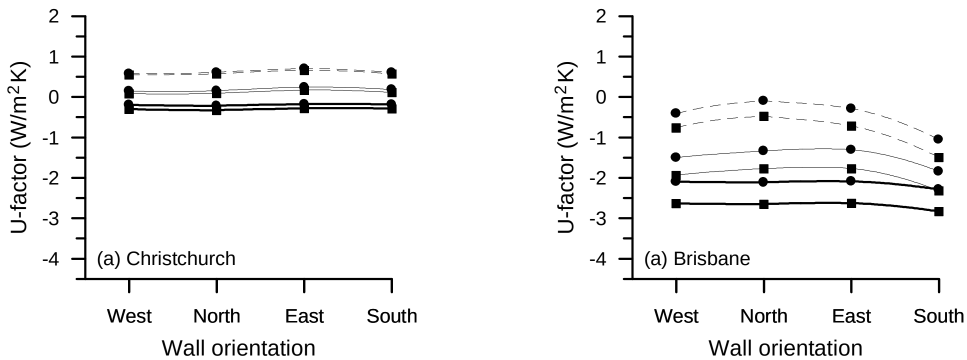

Figure 4. Equivalent U-factor of stratified concrete walls versus wall orientation (lightweight layer thermal conductivity equals 0.16 W/mK; heavyweight layer thermal conductivity equals 1.0 W/mK (●) or 1.8 W/mK (■); heavyweight layer thickness equals 100 mm; and panel thickness equals 200 mm (---), 250 mm (─) or 400 mm (━))

Table 3 shows that 250 mm thick stratified concrete walls in the model house achieve the net-zero energy performance target at all locations except Christchurch and Wellington. The EP≤0 target is nearly achieved at Wellington and is easily achieved at the warmer locations.

It is interesting to compare the results in Table 3 for the ‘low’ specification material with the ‘high’ specification material. The energy performance of ‘low’ specification material matches or outperforms the ‘high’ specification material at Sydney, Perth and Adelaide, and there is little difference between their energy performances at Auckland. At these locations it appears limited energy benefits are derived from a very low conductivity concrete in the lightweight layer or a very high conductivity concrete in the heavyweight layer. However, significant energy benefits are derived from using a ‘high’ specification stratified concrete at Christchurch, Wellington and Melbourne – the cooler locations.

4 Conclusion

This paper investigates the relationship between the design and energy performance of variable density concrete walls produced from stratified concrete, at eight temperate locations in Australia and New Zealand. Unsurprisingly, panel thickness is the main factor determining the energy performance of these walls. Increasing panel thickness increases wall insulation and thermal mass, both of which provide significant energy benefits in temperate locations.

It appears plain 250 mm thick stratified concrete walls can achieve net-zero energy performance at warmer locations (Melbourne to Brisbane), at least when used in the single-storey model house analysed in this paper. These walls appear well-suited to net-zero energy houses at these locations since they ‘pull their weight’ by reducing rather than adding to building energy use. Options for achieving net-zero energy performance at cooler locations (Christchurch and Wellington) include increasing panel thickness, adding supplementary insulation layers and/or adding ‘free’ heat to panels via embedded hydronic heating systems.

Heavyweight layer thickness and the thermal conductivities of lightweight and heavyweight layers appear to be secondary factors affecting the energy performance of stratified concrete walls, at least for the materials and locations considered here. Further research is required to better understand the effect of these factors on wall energy performance, especially at Mediterranean and sub-tropical locations where ‘low’ specification materials appear to outperform ‘high’ specification materials. This research will lead to the development of thermal design guides for variable density concrete walls produced from stratified concrete.

References

[1] Mackechnie, J.R. and Bellamy, L.A. (2013). Thermal Performance of Variable Density Wall Panels Made Using Portland Cement or Inorganic Polymer Concrete. *Materials and Structures (Online), October, 2013*.

[2] Bellamy, L. (2014). Towards the Development of New Energy Performance Indicators for the External Walls of Residential Buildings. *Energy and Buildings* **68/2014**, 696–702.

[3] Grynning, S., Gustaven, A., Time, B. and Jelle, B.P. (2013). Windows in the Buildings of Tomorrow: Energy Losers or Energy Gainers. *Energy and Buildings* **61/2013**, 185–192.